A PRELIMINARY STUDY OF THE EFFECT OF SUPPLEMENTAL IRRIGATION ON THE HYDROLOGY OF A WATERSHED

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Assisted by a grant from the
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FOREWORD

Despite North Carolina's long-term pre-eminence in agriculture, commercial irrigation in this state is only a recent phenomenon, dating from about 1950. It is used mainly to supplement rainfall for a few money crops, notably flue-cured tobacco. Despite its recent origin and rather limited scope, however, crop irrigation in this state is attracting widespread interest of farmers as a management practice and of other water users and public water agencies as a significant factor in the overall water economy. The practice of irrigation appears to be on the upswing, in the midst of a continuing growth phase.

Reliable data concerning irrigation in North Carolina--and, it goes without saying, advanced analytical or evaluative studies on irrigation practices--are in short supply. Before intelligent decisions can be made concerning the proper role of irrigation in North Carolina's overall water economy, a great deal remains to be learned about such matters as the feasibility of irrigating various crops in North Carolina, the potential for expansion of irrigation, the effects of irrigation upon other water uses, and the value of water used in irrigation as compared with other water uses. The study reported in this paper focuses on one of these gaps in knowledge: information relating to the physical effects of irrigation upon storage requirements for downstream water users.

This paper is one of a series of monographs that are the product of a long-term research program on water using arrangements in North Carolina--a program undertaken in 1962 under my supervision by the Institute of Government, with the aid of a grant from the United States Public Health Service. The author of this paper, Dr. Edward Wiser of the faculty of North Carolina State University, as an extension of his general research concerning the hydrology of small watersheds, undertook this study of the effects of supplemental irrigation on small watershed hydrology. His methodology involved using computor simulation models to estimate the hydrologic effects of irrigation in two hypothetical watersheds, designed to imitate the characteristics of two actual watersheds in Guilford County. His principal findings suggest the advantages of irrigation from ponds over irrigation from streams, in terms of effects on downstream water uses. They also point towards the relatively minor effects of irrigation, what-

ever its source, upon downstream storage if requirements for downstream releases from storage are small; and by implication, the relatively larger and competitive effects of irrigation, even from ponds, where requirements for downstream releases are substantial.

These findings may contain no surprises, but they do substantiate some previous assumptions and improve the basis for choice of irrigation sources. They also furnish tentative conclusions for further testing and exploration by subsequent researchers. Probably more important than the particular findings is Dr. Wiser's formulation and application of a methodology to be used and refined in analyzing and evaluating competitive water uses.

I am especially grateful for the opportunity afforded by this project for fruitful cooperation with faculty members on the Raleigh Campus of the University of North Carolina. An early benefit of this cooperation has been to help pave the way for creating and implementing a fully co-ordinated two-campus Water Resources Research Institute (WRRI), representing the Chapel Hill and Raleigh campuses of the University of North Carolina. An incidental reflection of the cooperative spirit of this endeavor is that the title of this monograph series (UNC Water Resource Papers) will be taken over by the WRRI upon completion of the studies supported by the United States Public Health Service which originated the series.

Milton S. Heath, Jr.
Institute of Government
Chapel Hill
November 1966

ABSTRACT*

Although surface water sources are generally adequate in areas where supplemental irrigation is practiced, conflicts for available water occasionally arise on specific watersheds. Such a conflict may develop when irrigators use water in a watershed being used for municipal or industrial water supply. Consumptive use by crops in presumed to result in a decrease in available streamflow.

Since a field study of the effect of supplemental irrigation on water supply is impractical, use was made of computer simulation models to estimate the effect. Water balance models were used on two hypothetical watersheds to simulate streamflow, both under natural climatic conditions and with irrigation. The source of irrigation water was assumed to be either wells, surface ponds or streamflow. Results were obtained in terms of the volume of storage required to maintain a specified discharge at the lower end of the watershed.

It was found that less than half of the water applied was actually lost from the watershed, the remainder appearing eventually in streamflow. Thus, irrigation from wells reduced the storage requirement. Since pond storage is usually replenished during months of excessive rainfall and the runoff intercepted by the ponds during the summer was more than compensated for by increased runoff from the irrigated area, irrigation from ponds had little effect on storage requirements, unless the required discharge was rather large. Irrigation from streamflow, however, had an appreciable effect on storage requirements since it is, in effect, directly removed from storage.

It is also possible to compare cost of increased storage with increased crop value due to irrigation in order to select economically best use of the water supply in a given watershed. The results obtained at this time must be considered preliminary since improvements in the simulation techniques may be expected.

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*This paper is also being published by the North Carolina Agricultural Experiment Station as Paper No. 2305 of its Journal Series.

INTRODUCTION

Water is generally available in abundant supply in the eastern United States, but shortages are occurring with increasing frequency. These shortages may occur as the result of either of two factors. First, natural variation in rainfall through time occurs such that extended dry periods can be expected. Second, demand for water is sometimes allowed to concentrate in locations where the supply is deficient.

One region of North Carolina in which such problems may arise is the area around Greensboro. This area lies in the headwaters of the Cape Fear River, and there is no single satisfactory source of water. Ground water supplies are generally unsatisfactory. The municipalities and industries therefore depend primarily on surface water supplies from relatively small (largely agricultural) watersheds.

At the same time, there may be an increase in use of supplemental irrigation in the area. This would be partly from an increasing appreciation on the part of farmers of the benefits to be derived by irrigating, and partly from an increase in specialties such as truck cropping and nurseries stimulated by the expanding metropolis.

The increased use of water for irrigation would be expected to affect the amount of water available for municipal and industrial supplies. However, this effect cannot be measured simply in terms of the irrigation application. There is, certainly, an overall loss to the basin due to increased evapotranspiration. On the other hand, the high moisture contents maintained under irrigated conditions must result in higher runoff rates during the dry months. If the water being applied has been stored during periods when it would otherwise have been lost, an increase in streamflow might be expected.

The purpose of this study is to determine the effect that supplemental irrigation has on the downstream water supply. It would also be desirable to identify practices which minimize this effect. Quantitative answers could also be used to select between various uses of water in a river basin.

PROCEDURE

The hydrologic effect of supplemental irrigation could be examined by field study of actual watersheds only with great difficulty. Such a study would have to be carried out on a single watershed for a number of years,

with and without irrigation. The results obtained would be appropriate only to watersheds similar in all respects to the watershed studied.

A reasonable alternative is to simulate a watershed on a computer. Models have been developed for this purpose by a number of investigators, and have been shown to lead to reliable results. An acceptance of the results obtained in this way depends largely on faith in the manner in which the relatively simple model mirrors the actual behavior of a complex watershed. At this time, the models in use are too oversimplified to use for models of specific watersheds, although they can be used for hypothetical watersheds which have similar characteristics to specific watersheds.

The results that have been obtained have been sufficiently encouraging to justify their use for the problem to be studied here. To the extent that the models may be expected to undergo a great deal of improvement, this study must be considered preliminary in nature, the results being used more to show the type of results that are obtained than to be used as quantitatively correct values.

The simulation used in this study was based on two water balance models which had been developed for other purposes. One model, used to simulate the watershed as a whole had been developed to estimate daily streamflow (4). This model uses basically a water balance of the soil profile, with surface runoff computed as a function of the moisture content in the upper layers of the profile, and percolation through the profile used to replenish ground water storage, GWS. Base flow discharge, QG, is then obtained as a linear function of GWS, i.e. $QG = C \times GWS$, and added to the surface runoff to obtain streamflow for a given day. The constant C is a function of the storage characteristics of the watershed, and may be estimated from the ground water recession curve.

The second model is used to simulate the irrigation practice (5). It is also a model of the soil profile such that whenever the soil moisture content reaches a specified minimum, an irrigation is simulated. The irrigation amount is chosen so that the soil moisture content is returned almost to field capacity. Combined with the other model to simulate an irrigated watershed, some surface runoff was computed from the irrigation, but this amount was deducted from the final results for streamflow and not considered further. The model therefore simulates a perfectly efficient irrigation, whose only loss is an evaporation loss which is calculated as potential evapotranspiration.

The first model could be run alone to simulate a watershed without irrigation, and then the two models could be combined to simulate an irrigated watershed. Daily weather data used in the simulation were taken from records for the Greensboro airport for the years 1934-1958, a 25-year period.

Some additional assumptions were required in order to use the models, and these may be considered to be characteristics of the watershed:

1) The watershed model required an estimate of the maximum soil moisture storage capacity. Previous studies of the East Fork watershed in the area of interest had indicated a capacity of 12 inches.

2) Calculation of the base flow discharge required estimates of the constant C. For two watersheds in the study area, East Fork and Stony Creek, values were estimated as 0.01 and 0.044 respectively.

3) The field capacity used for the irrigation model was estimated to be 4 inches. An irrigation application of 1.25 inches was simulated, but since some of this water was counted as surface runoff and eliminated from the model, an average application of 1.09 inches remained.

4) 30% of the watershed was assumed to be irrigated, and the entire irrigation application was assumed to occur on the same day. Irrigation was restricted to the period May 15 - August 15.

5) It was assumed that results for a partly irrigated watershed could be obtained by weighting the results for irrigated and non-irrigated watersheds, without considering any possible interactions.

6) Sources of water for irrigation were:

   a) Deep wells, with no recharge from the watershed;

   b) Streamflow, the entire flow being assumed usable;

   c) Surface ponds which collect surface runoff only from 40% of the total watershed, of the 70% which is not irrigated.

7) The hydrologic effect of irrigation on the downstream user is summarized by the storage requirement necessary to maintain a specified discharge downstream. The maximum storage for any treatment was calculated by the Rippl method, which gives a storage value which would have been sufficient for the 25-year period of record. Presumably, data generation could have been combined with the simulation to obtain a storage - frequency relation, but this refinement was not used in this study.

RESULTS

All numerical results are reported in watershed inches. For example, the average annual irrigation application was 5.16 inches, but this is equivalent to 1.55 watershed inches since only 30% was irrigated.

Some annual average values for C=0.01 are given in Table I. The values for C=0.044 differ only slightly because of different carryover values at the end of the 25-year period. The increase in runoff due to irrigation from wells is equal to the irrigation amount less the increased loss. The decrease in runoff due to irrigation from streams or ponds is equal to the increased loss.

It may be noted that of the 1.55 inches of irrigation water applied, only 0.69 inches or about 45% were actually lost by increased evapotranspiration. This is particularly surprising when it is recalled that the simulator assumed efficient application. What happens is that less precipitation is lost from the basin and part of the water applied by irrigation remains at the end of the season as increased soil moisture storage.

It may also be noted that irrigation from wells increases annual runoff. Since most of this increase occurs during the summer months, it is a desirable practice under any circumstance, as far as the downstream user is concerned. Thus, our attention will be limited to the effect of irrigation from streams and ponds.

The effect of these two sources of water is illustrated in Table II, as well as in Figures 1 and 2, in which the storage requirement is given as a function of required discharge. Data are also plotted as obtained for the period of record for the two streams used in obtaining the constants C. Since the period of record for the observed records is different from the simulated records, a comparison of the observed with the simulated results is useful only to indicate that the simulators yield quantitatively useful data.

A comparison between requirements for a specific discharge shows that the most important single factor is the storage characteristic of the watershed as it affects the constant C. An examination of water - supply characteristics of a number of streams in the area (3), indicates that the two streams used are unusual, East Fork having very good characteristics and Stony Creek having very poor characteristics. Thus, the effect of irrigation on other streams in the area is presumably intermediate between the two.

It will be noted from the results that irrigation from streams causes an increase in storage requirement at all discharge levels. This might be expected, since the irrigation is effectively using the storage for a source. In fact, there was not enough streamflow to supply water at all times for irrigation, and additional storage would have been necessary. For the particular 25-year period, this would have amounted to 0.42 inches for C=0.01, and 1.37 inches for C=0.044. This is a considerable amount of storage which would have to be provided effectively in addition to the storage necessary for maintaining downstream requirements.

Irrigation from ponds had no appreciable effect on storage requirements unless the required discharge was as much as 0.6 inches per month. At the lower requirements, the increased streamflow during the summer evidently compensated for interception of runoff by the ponds during the dry months. However, when the storage requirement becomes large enough, it is not refilled during every winter season. This is illustrated by Table III, in which are given the maximum lengths of periods during which there was not enough water to fill the required storage.

It is evident that, for discharge requirements over 0.6 inches per month, the storage is not refilled every winter. In such a case, the ponds are in direct competition with the downstream storage, and the effect of irrigation becomes apparent.

An additional result of this study was the figure for watershed area of the ponds given previously as an assumption. It was in fact first assumed that 30% of the total area should be sufficient to supply water for the 30% irrigated. However, it was found that ponds would be prohibitively large under this assumption. Under the assumed 40% value, the required storage capacity of the ponds for the 25-year period was 2.14 watershed inches for either value of C.

DISCUSSION

Some comparisons with actual systems may be useful in determining practical implications of the results. As an example, the Greensboro municipal water supply consists of two lakes having a combined drainage area of 70 square miles. Their total capacity is 401 million cubic feet, equivalent to 2.47 watershed inches. Average use by the city (2) was 24.3 cubic feet

per second, or 0.40 inches per month. Assuming Figure 1 to be valid in this case (East Fork is immediately adjacent to the Greensboro watershed) the present storage capacity would be sufficient to provide a regulated monthly discharge of 0.66 inches without irrigation, 0.60 inches with irrigation from streams and 0.58 inches with irrigation from ponds. At this level of use irrigation has an appreciable effect on the available discharge.

Since at this high rate of use recreational benefits from the lakes would also be reduced, the city might alternatively construct other lakes, with the present lakes being used at their present level of 0.40 inches per month, remaining capacity being maintained for recreation and emergency supplies. The minimum storage in the lakes would then be 1.67 inches without irrigation (2.47-0.80), 1.57 inches with irrigation from ponds and 1.27 inches with irrigation from streams. In this case, only irrigation from streams would have an appreciable effect.

The City of Burlington has two lakes in the Stony Creek watershed. Their combined storage capacity is 2.23 inches with a use rate of 0.12 inches per month. The present capacity would be sufficient to maintain a monthly discharge of 0.40 inches without irrigation, 0.38 inches with irrigation from ponds and 0.29 inches with irrigation from streams. In this case, irrigation from ponds would have a negligible effect on municipal supplies.

Another possible use of the simulation procedure may be illustrated by consideration of the proposed Randleman dam (1). The East Fork lies within the watershed of this dam. Present storage allocations are for 3.0 inches of storage for water supply and 2.8 inches for water-quality control, or a total of 5.8 inches. According to Figure 1, these storage allocations should be enough to maintain discharges of 0.70 inches (106 cfs) for water supply, 0.69 inches (104 cfs) for water-quality control, or 0.86 inches (130 cfs) for both. The latter figure simply verifies the fact that the two storage allocations cannot be operated separately to give the desired discharges.

If irrigation from ponds was to develop over 30% of the watershed, two alternatives would be possible:

1) At the design storage capacity, a discharge of only 0.77 inches could be maintained;

2) By increasing the storage capacity to 7.4 inches, a discharge of 0.86 inches could be maintained.

By determining the increased crop value due to irrigation, the cost of a reduction in discharge, and the cost of an increase in storage, it should be possible to choose the economic alternative. Note that under the first alternative, the value of 1.08 (=12 x 0.09) inches of increased discharge is to be compared with the value of the average annual irrigation amount of 1.55 inches.

CONCLUSION

It may again be emphasized that the results given are used to illustrate the type of results that may be expected from a study of the effect of supplemental irrigation, and to show some of the ways in which the results might be of use. The particular values given are subject to inaccuracies resulting from failure of the models to match the real watersheds for which estimates must be made.

It is believed, however, that the results are sufficiently reliable to draw certain conclusions, particularly when comparative results for the hypothetical watersheds are considered. The principal result is that irrigation has a relatively minor effect on storage requirements when the storage requirements themselves are not large. This is particularly true for irrigation from ponds. It does not seem to be influenced by storage characteristics of the watershed.

It is also evident that irrigation from streams is a less desirable practice, since downstream storage requirements are increased, and supplemental storage is necessary.

There are undoubtedly other watershed factors which might influence the findings of this study. In particular, the location of the irrigated areas of the watershed could affect the results appreciably if they are concentrated near, or far from, the stream, or if they have unusual soil or topographic characteristics. Models now available are not sufficiently sophisticated to treat such irregularities. However, refinements can certainly be expected which will yield more reliable results.

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TABLE I

AVERAGE ANNUAL VALUES

	Amount Watershed Inches
Total runoff:	
No irrigation	14.82
Irrigation from wells	15.68
Irrigation from streams	14.13
Irrigation from ponds	14.14
Irrigation amount	1.55
Increased loss due to irrigation	0.69

TABLE II

MINIMUM STORAGE REQUIREMENTS

Required Discharge, inches per month	C=0.01 Irrigation Source			C=0.044 Irrigation Source		
	None	Stream	Pond	None	Stream	Pond
0	0	0	0	0	0	0
.1	0	.30	.01	.40	.70	.40
.2	.16	.60	.17	.85	1.43	.99
.3	.46	.90	.47	1.55	2.33	1.69
.4	.77	1.20	.88	2.25	3.23	2.39
.5	1.33	1.73	1.47	2.95	4.13	3.09
.6	1.93	2.43	2.76	3.67	5.03	4.41
.7	2.93	3.72	4.48	4.97	6.41	6.41
.8	4.73	5.63	6.28	6.97	8.41	8.41
.9	6.53	7.63	8.08	8.97	10.41	10.41
1.0	8.33	9.63	9.88	10.97	12.41	12.41

TABLE III

CONSECUTIVE MONTHS OF DEFICIENT STORAGE

Required Discharge, inches per month	C=0.01	C=0.044
0	0	0
.1	0	6
.2	2	7
.3	5	8
.4	5	9
.5	7	18
.6	18	21
.7	20	22
.8	21	23
.9	33	35
1.0	38	45

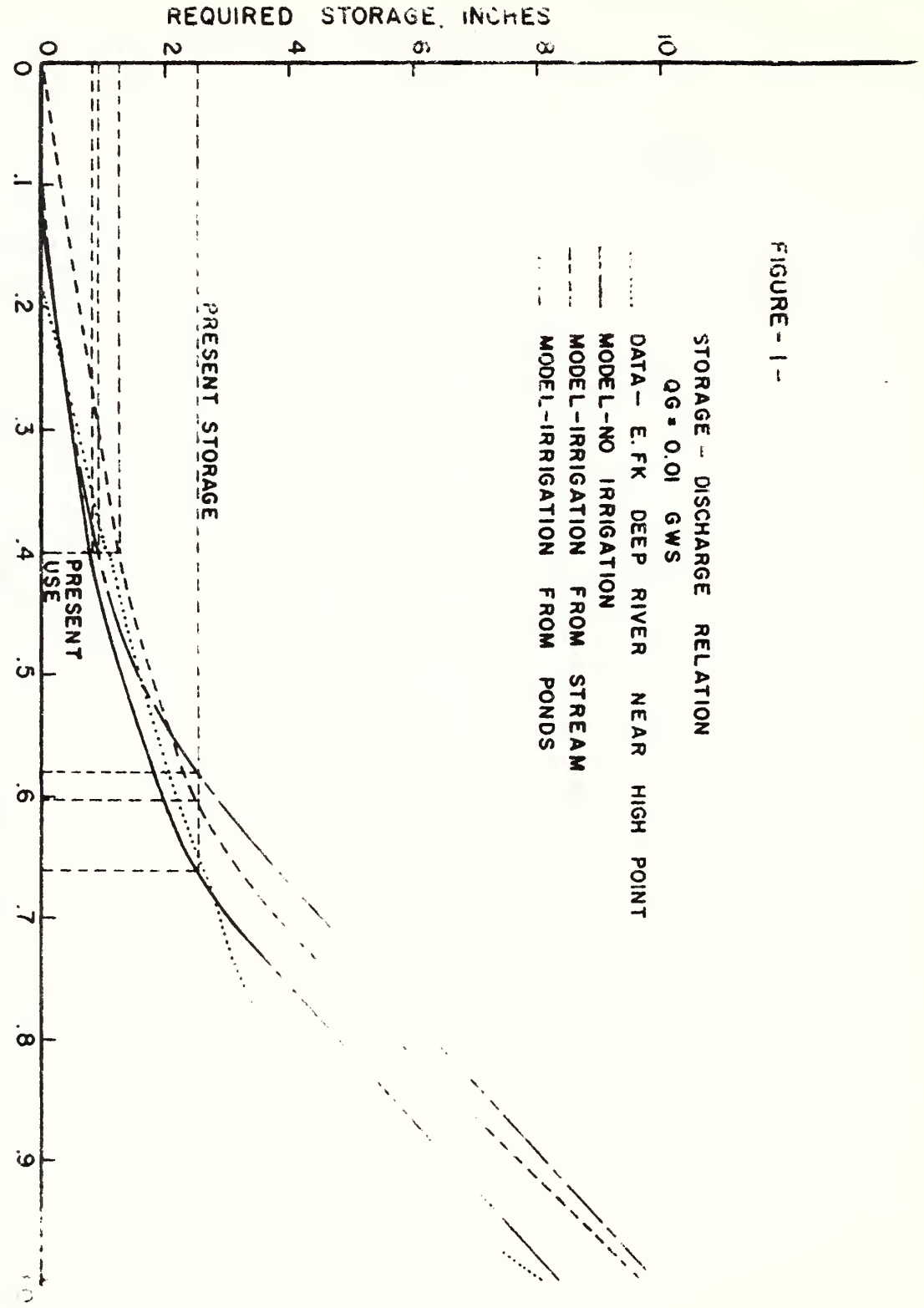
REQUIRED STORAGE, INCHES
0
2
4
6
8
10
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
PRESENT STORAGE
PRESENT USE
REGULATED MONTHLY DISCHARGE, INCHES
STORAGE - DISCHARGE RELATION
QG = 0.01 GWS
DATA— E. FK DEEP RIVER NEAR HIGH POINT
MODEL-NO IRRIGATION
MODEL-IRRIGATION FROM STREAM
MODEL-IRRIGATION FROM PONDS

FIGURE - 1 -

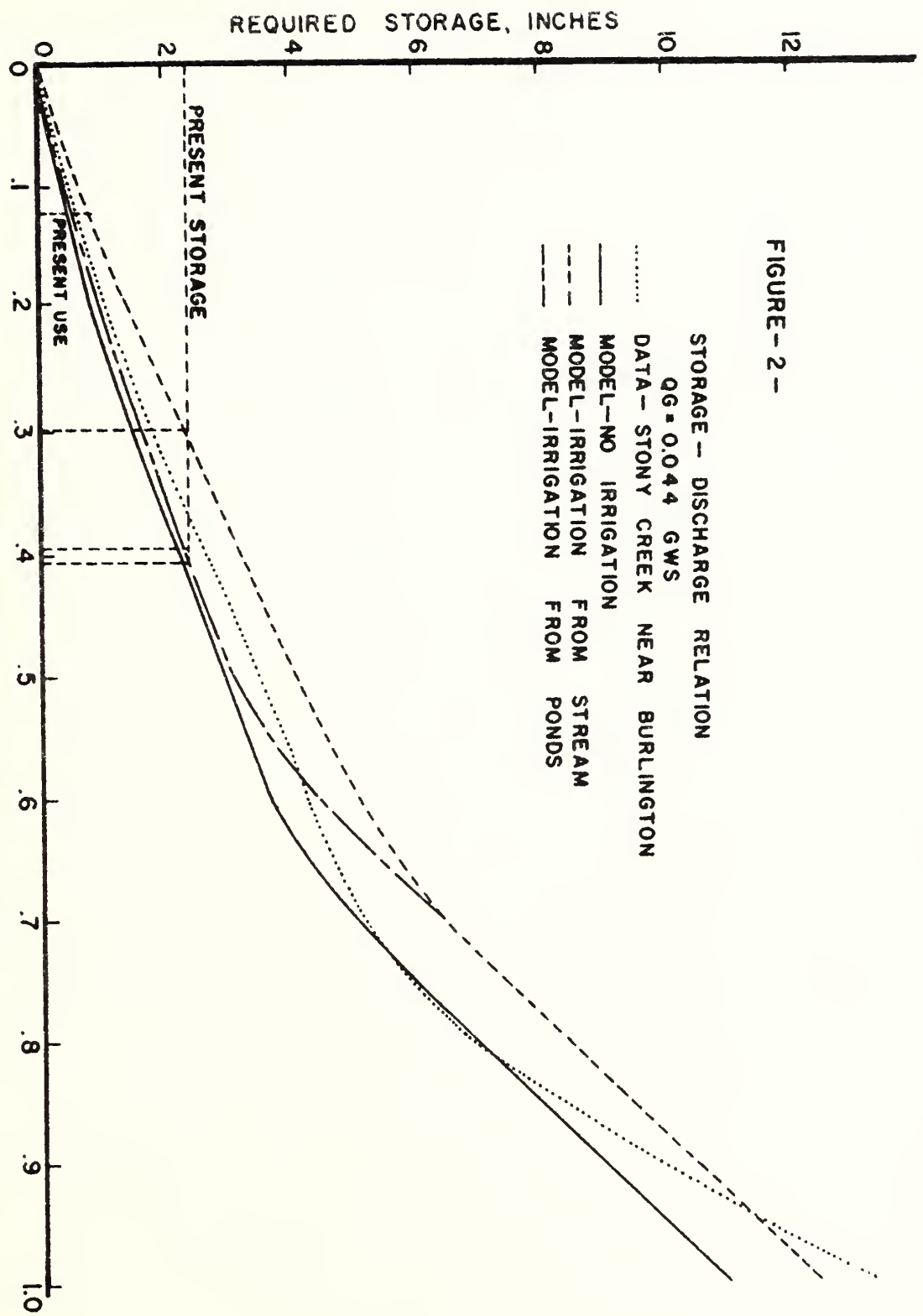
REQUIRED STORAGE, INCHES
0
2
4
6
8
10
12
PRESENT STORAGE
PRESENT USE
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
REGULATED MONTHLY DISCHARGE, INCHES
STORAGE -- DISCHARGE RELATION
QG = 0.044 GWS
DATA- STONY CREEK NEAR BURLINGTON
MODEL—NO IRRIGATION
MODEL-IRRIGATION FROM STREAM
MODEL-IRRIGATION FROM PONDS

FIGURE-2-